

A Sensitive Wavelet-Based Algorithm for Fault Detection in Power Distribution Networks

N. Zamanan M. Gilany
College of Technological Studies,
Dept. of Electrical Engineering,
Kuwait
W. Wahba
Faculty of Engineering,
Faoum University,
Egypt

Abstract—This paper presents a wavelet based technique for detection and classification of abnormal conditions that occur on power distribution lines. The transients associated with these conditions contain a large spectrum of frequencies, which are analyzed using wavelet transform approach. The proposed technique depends on a sensitive fault detection parameter (denoted *SFD*) calculated from wavelet multi-resolution decomposition of the three phase currents. The simulation results of this study clearly indicate that the proposed technique can be successfully used to detect not only faults that could not be detected by conventional relays but also abnormal transients like load switching and inrush currents.

Keywords— Wavelet Transform, Fault detection, Distribution Networks, Inrush currents.

I. INTRODUCTION

Power disturbance occur due to changes in the electrical configurations of a power circuit. Disturbance causing failure are infrequent compared to the number of disturbances that occur every day due to normal system operations (switching of lines, switching on/off generating units, or switching of capacitor banks to balance inductive loads). In order to improve electrical power quality, one must have the ability to detect and classify these disturbances. There are two main problems related to protection of distribution networks.

1. The first problem is the faults through high resistance. These faults are not easy to be detected, since the fault current may not reach the setting of the relay. It may cause successive heating and fires unless the fault is isolated.
2. The second problem is the numerous cases of power system transients (like switching) which may cause transient responses similar to that induced by the permanent faults. It is hence necessary to identify the disturbance type and classify it in order to have a high reliability levels.

The waveforms associated with these transients are typically non-periodic signals, which contain both high frequency oscillations and localized impulses superimposed on the power frequencies. In order to extract or separate these

superimposed signals, several algorithms have been introduced in power system such as Kalman filtering, least square method, and Fourier transform. However, in presence of non-stationary signals, the performance of these algorithms is limited and this is the introduction to the need of wavelet transform (WT).

The idea of application of wavelet transform analysis to fault detection in power systems is not new and there are hundreds of publications related to this idea. The wavelet-based techniques are applied in different power system applications such as detecting arcing faults in distribution systems [1], locating SLG faults in distribution lines [2], stator ground fault protection schemes with selectivity for generators [3], locating faults in transmission systems [4,5], locating faults in systems with tapped lines [6] and solving inrush current problems [7,8].

Application of wavelet transform in protection of distribution networks faces two main difficulties that have limited the usefulness of these techniques. The first difficulty is that the transient levels in distribution circuits are generally small compared with that in HV transmission networks. The second difficulty faces the application of wavelet transforms in protection of distribution networks is the need to add extra components (e.g. VTs) to the existing distribution protection systems in order to apply such techniques. Analyzing voltage waveforms is much easier than current waveforms due to the large content of harmonics in voltage waveforms. Most researchers are using both current and voltage samples of the three phases as inputs for fault detection in order to overcome this difficulty [1,2,3,6,7,8]. However, many distribution systems are not provided with voltage transformers since they are using overcurrent relays. Other researchers use extra hardware like GPS to improve the usefulness of these techniques [6, 9].

A sensitive parameter (denoted *SFD*) is used in this paper to detect and classify faults in distribution networks under different operating conditions including low-current faults and arcing faults. The technique can also be used to discriminate between the transients due to switching-on additional loads and that due to 3LG faults through high resistance. In all cases, the proposed technique is not affected

with the above mention two limitations (low harmonic contents or need for voltage signals). It also discriminates between the inrush currents and fault currents. In the next section, a theoretical background of wavelet theory is reviewed. The proposed algorithm and the simulation results are then presented in the subsequent sections.

II. THEORETICAL BACKGROUND

In order to extract certain information from a given signal, mathematical transformations are required. WT is very well suited for wideband signals that are not periodic and may contain both sinusoidal and impulse transients, as is typical in power system transients. In particular, the ability of wavelets to focus on short-time intervals for high frequency components and long-time intervals for low frequency components improves the analysis of signals with localized impulses and oscillations, particularly in the presence of fundamental and low-order harmonics [9].

The Wavelet Transform (WT) of a continuous time domain signal $f(t)$ is defined as:

$$WT(f, a, b) = \frac{1}{\sqrt{a}} \int_{-\infty}^{\infty} f(t) \Psi\left(\frac{t-b}{a}\right) dt \quad (1)$$

Where a is the scale constant (dilation) and b is the translation constant (time shift). The $\Psi(t)$ is the wavelet function that is short, oscillatory with zero average and decays quickly at both ends. This property of $\Psi(t)$ ensures that the integral in equation (1) is finite and that is why the name wavelet or “small wave” is assigned to the transform. The term $\Psi(t)$ is referred to as the “mother wavelet” and its dilates (a) and translates (b) simply are referred to as “wavelets”.

Wavelets have a window that is automatically adapted to give an appropriate resolution. The window is shifted along the signal and for every position the spectrum is calculated. This process is repeated many times with a slightly shorter (or longer) window for every new cycle. At the end of this process, the result will be a collection of time-frequency representations of the signal, all with different resolutions. Because of this collection of representations we can speak of a multi-resolution analysis (MRA) [10].

The wavelet transform given by Eq. (1) has a digital counterpart known as the Discrete Wavelet Transform (DWT). The DWT is defined as

$$DWT(f, m, n) = \frac{1}{\sqrt{a_0^m}} \sum_k f(k) \Psi^*\left(\frac{n - ka_0^m}{a_0^m}\right) \quad (2)$$

where the parameters a and b in Eq. (1) are replaced by a_0^m and $(k a_0^m)$. The parameters k and m are integer variables.

The actual implementation of the DWT involves successive pairs of high-pass and low-pass filters at each

scaling stage of the wavelet. The successive stages of decomposition are known as levels or details (denoted detail_1 or d1 for short, detail_2 or d2 for short, etc.). The multi-resolution analysis, MRA details at various levels contain the features that can be used for detection and classification of faults. More details about wavelet transform can be found in [11-12].

The choice of mother wavelet, $\Psi(t)$ plays a significant role in detecting and localizing different types of fault transients. Each mother function has its own features depending on the application requirements. The proposed technique is depending on detecting and analyzing low amplitude, short duration, fast decaying high frequency current signals. In this study, Daubechies wavelets (D4) is chosen since it is effective for the detecting fast and short transient disturbances [13].

III. THE PROPOSED ALGORITHM

In the proposed technique, the wavelet transform is firstly applied to decompose the three phase current signals into a series of detailed wavelet components, each of which is a time domain signal that covers a specific frequency band, hence the time and frequency domains features of the transient signals are extracted.

Wavelet analysis involves selection of an appropriate wavelet function called “mother wavelet”. The choice of mother wavelet plays a significant role in detecting and localizing different types of fault transients. Each mother function has its feasibility depending on the application requirements. In this study we are interested in detecting and analyzing low amplitude, short duration, fast decaying and oscillating type of high frequency current signals. One of the most popular mother wavelets suitable for such applications is the daubichies’s wavelet. In this paper, D4 wavelet is used for the analysis of the current waveforms.

For each cycle, the detail signals d1 and d2 of each of the three-phase currents are calculated. The sensitive fault detection parameter used in this work, SFD is a moving average filter for the summation of the squared of d1 and d2 of the three phase currents. Involving only two levels details ensures less computational burden and fast speed. This parameter is calculated as follows:

$$SFD_p(k) = SFD_p(k-1) + \sum_{h=1}^2 d_p^2(k) - \sum_{h=1}^2 d_p^2(k-n), \quad p \in (a, b, c) \quad (3)$$

where n is the number of samples in the window, h is the suffix for the detail order (1 or 2) and $p = (a, b, c)$ are suffixes used for phases.

A fault is detected if the value of SFD exceeds a threshold setting (equal to 300 in this study). This threshold is selected according to the detail values in normal and fault operations. The previously-mentioned limitations for applying wavelet in distribution networks are reduced in the

proposed technique for the two following reasons:

The proposed technique concentrates on the noise frequency of the signal not on the noise amplitude. The proposed technique uses the parameter SFD over one cycle of the current signal which is very sensitive to any small changes in the current signal since it uses the squared of the first and second details of the decomposed signals.

IV. MODELING OF POWER SYSTEM

The power system under study was modeled using the Matlab power system toolbox. Simulations for fault analysis are carried out on the low voltage side of a 66/11 KV transformer connected to two 20 km-feeders. The 20 km overhead feeder is modeled using the distributed parameters. A sampling rate of 20 kHz is used, which covers the range of frequencies from 10 kHz to DC. To prove the sensitivity of the proposed technique, all the simulation studies are done with fault current magnitudes lower than the typical overcurrent relay settings. Some fault cases are carried out with a fault current lower than the normal load current. Only the three phase current signals are used in order to avoid adding extra components (voltage transformers) to the typical existing protection system in distribution networks.

V. SIMULATION RESULTS

Intensive simulations for a large number of case studies were carried out, taking into consideration different normal and abnormal conditions. The simulation study using Matlab is adopted to generate the current signals of the power system under study. The current signals are then decomposed into different levels of frequencies. The SFD (given in A^2) is calculated using only *detail_1* and *detail_2* for each phase. The predetermined threshold is compared to the calculated SFD and accordingly, the fault is detected and classified. The performance of the proposed technique under different conditions is illustrated in the following sub-sections.

A. High resistive SLG faults

In this case, a SLG fault is simulated at a distance of 10 km. The fault resistance is chosen, such that the fault current does not exceed 200% of the rated load current. This is the typical pickup setting for ordinary overcurrent relays. The details ($d1$ and $d2$) of the faulty phase current is shown in Fig. 1, where that of a healthy phase (phase-B as an example) are shown in Fig. 2.

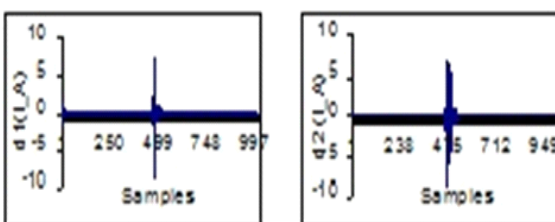


Fig. 1: Detail_1 and detail_2 for the faulty phase (SLG fault)

The waveforms of the healthy phases may contain high frequency signals due to mutual coupling as shown in Fig. 2. The SFD of the healthy phase is very small compared to that of the faulty phase as shown in Fig. 3.

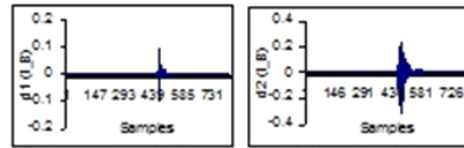


Fig. 2: Detail_1 and detail_2 for a healthy phase (SLG fault).

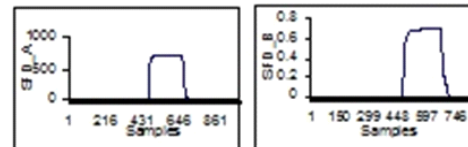


Fig. 3: The SFD for the faulty and a healthy phase for a SLG fault.

B. High resistive 3LG fault

In this case, a (3LG) fault is considered. To add more difficulties to this fault case, it is assumed that the fault occurred near to the far end of the feeder (at a distance of 18 km from the sending end). The inception angle is 120° . The three phase currents are shown in Fig. 4. The corresponding wavelet details for one of the three faulty phases are shown in Fig. 5.

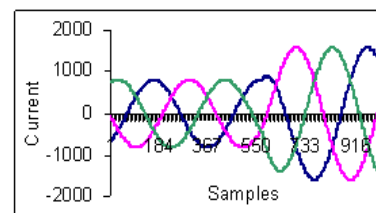


Fig. 4: The three phase currents for 3LG fault.

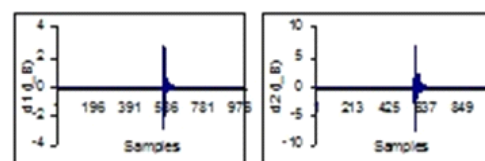


Fig. 5: The decomposition for one of the three phase currents (for 3LG fault).

The SFD for this case is shown later in Fig 7(a2, b2, c2) in order to be compared with the case presented in the next subsection (switching on additional load).

C. Load switching

Transients may be initiated due to switching operations e.g. when adding a new load to the system. Discrimination between the transients generated due to switching condition and that due to faults is of great importance. Figure 6 shows the waveforms of the three phase currents during switching condition. The inception angle was chosen to be 120° to create some sort of analogy between this switching condition and the case presented in the previous section (3LG fault).

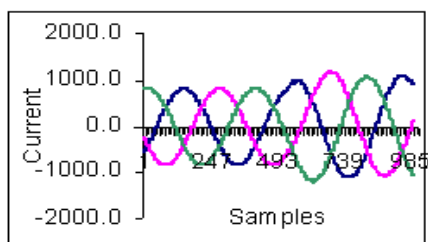


Fig. 6: Three phase currents for load switching

The similarity between the two cases is more critical if the low frequency signals are considered, and hence, a false trip may not be avoided. The proposed technique avoids this problem since the proposed technique uses only the high frequency signals (details 1-2 only).

The SFD of these frequency bands (shown in Fig. 7(a1, b1, c1)) are less than the predetermined threshold, therefore such cases will be recognized as switching conditions and not fault conditions since all of the SFDs exceeds the threshold (Threshold = 300).

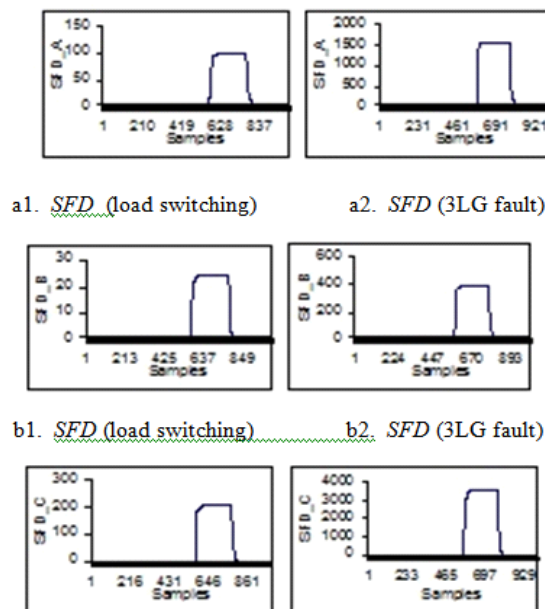


Fig. 7: A Comparison between the SFD for 3LG fault and the SFD for load switching

D. Discrimination between Permanent Faults and Inrush currents

When a transformer is switched off, its core generally retains some residual flux. Later, when the transformer is re-energized, the core is likely to saturate. If it does, the primary windings draw large magnetizing currents from the power system. This phenomenon is known as magnetizing inrush and is characterized by the transformer drawing large currents from the source but supplying relatively smaller currents to the loads. This results in a large differential current which causes differential relay to operate. But it is not a fault condition, and therefore the relay must be able to discriminate inrush current from internal fault current, and remain stable during inrush current.

To date, there are many discrimination methods [7,8,14,15]. Each of these methods has its own shortcoming. For the second harmonic restrained method, under some special conditions, such as when the power transformer is connected to a long transmission line, or when the current transformer (CT) is saturated, the second harmonic component of the transformer current will increase, thereby affecting the operation of the relay.

In this paper, the sensitive SFD parameter is examined against this problem. The results show that tracing the value of this parameter gives an excellent index for the discrimination between the permanent faults and inrush currents as shown in the following results.

The inrush condition is simulated at different inception angles to almost cover all possible inrush current waveforms. Figure 8 shows the waveforms of one of the phase currents (IA). The inception angle is assumed to be zero. The decomposed signals (details) of the discrete wavelet transform are shown in Fig. 9.

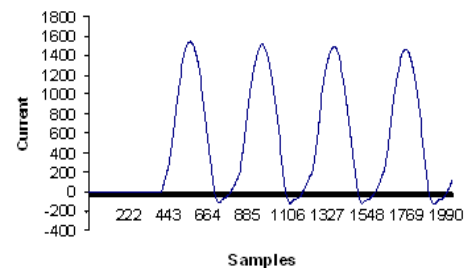
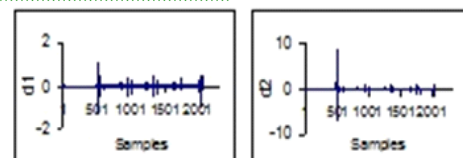


Fig. 8: A typical inrush current case

As can be seen from Fig. 9 that the current waveform is distorted quite significantly.



9. Detail_1 and detail_2 for inrush current in phase-A with zero inception angle.

The existence of the higher frequency signals superimposed on the fundamental can clearly demonstrated by wavelet transform. In this study, details 1-2 are only the ones employed in the analysis and feature extraction. For inrush condition, the high frequencies are of small magnitude compared with low frequencies. This feature is so important in the discrimination between internal faults and inrush currents. The value of SFD for all the examined cases will be below the setting threshold value as shown in Fig. 10.

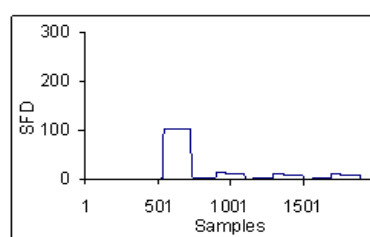


Fig. 10. The *SFD* for phase-A (inrush current case)

VI. CONCLUSIONS

Distribution feeders are subjected to all types of faults. Detection of these faults and discriminating it from other transient conditions such as switching is of great importance. These faults can occur through resistances, that make the fault current not in the range of the setting of conventional relays and hence the fault will be not easy to be detected. The use of wavelet transform with the proposed sensitive *SFD* parameter makes it easy not only to detect the occurrence of a fault and its type but also to discriminate between transients due to switching conditions/inrush currents and that due to faults. A subroutine is designed to detect arcing faults in which the level of fault current is very small. Lots of simulation results show that the proposed method can exactly and effectively detect and classify both normal and abnormal conditions in the distribution networks.

ACKNOWLEDGMENTS

The financial support from the PAAET in Kuwait (Project No. TS-09-02) is highly appreciated.

REFERENCES

- [1] Marek Michalik, Miroslaw Lukowicz, Waldemar Rebizant, Seung-Jae Lee, and Sang-Hee Kang, "Verification of the Wavelet-Based HIF Detecting Algorithm Performance in Solidly Grounded MV Networks", *IEEE Trans. Power Delivery*, Vol. 22, No. 4, Oct., 2007 pp. 2057-2064.
- [2] Fan Chunju, K.K. Li b, W.L. Chan, Yu Weiyong, Zhang Zhaoning, "Application of Wavelet Fuzzy Neural Network in Locating Single Line to Ground Fault (SLG) in Distribution Lines", *Electrical Power and Energy Systems*, 29 (2007), pp. 497-503.
- [3] Tai Nengling, Chen Jiajia, "Wavelet-Based Directional Stator Ground Fault Protection for Generator", *Electric Power Systems Research* 77 (2007), pp. 455 - 461.
- [4] D. Chanda, N.K. Kishore, A.K. Sinha, "A Wavelet Multi-Resolution Analysis for Location of Faults in Transmission Lines", *Electric Power and Energy Systems*, 25(2003), pp. 59-69.
- [5] "IEEE Guide for Determining Fault Location on AC Transmission and Distribution Lines", *IEEE Standard C37.114*, December 2004.
- [6] Nouri H, Wang C, Davies T. "An Accurate Fault Location Technique for Distribution Lines with Tapped Loads Using Wavelet Transform", *Proc of IEEE Power Tech Porto* Sept. 2001, pp. 10-13.
- [7] Pablo Arbolea, Guzman Diaz, Javier Goez-Aleixandre, Cristina Gonzalez, "A Solution to the Dilemma Inrush/Fault in Transformer Differential Relaying Using MRA and Wavelets", *Electric Power Components and Systems*, 34, 2006, pp. 285-301.
- [8] A.R. Sedighi, M.R. Haghifam, "Detection of Inrush Current in Distribution Transformer Using Wavelet Transform", *Electric Power and Energy Systems*, Vol. 27, 2005, pp. 361-370.
- [9] Car L. Benner and B. Don Russel, "Practical high impedance fault detection on distribution feeders", *IEEE Trans. On Industry Applications*, Vol. 33, No. 3, May/June 1997.
- [10] S. R. Nam, J. k Park, Y. C. Kang, and T. H. Kim, "A Modeling method to a high impedance fault in a distribution system using two series time-varying resistances", *IEEE Trans. On PES*, 2001, pp. 1175-1180.
- [11] Chul Hwan Kim and Raj Aggarwal, "Wavelet Transform in Power Systems, Part1: General Introduction to the Wavelet Transform", *IEEE Tutorial, Power Engineering Journal*, Vol.14, Issue 2, April 2000.
- [12] Wilkinson, W.A and Cox, M.S., "Discrete Wavelet Analysis of Power System Transients", *IEEE Trans. Power Systems*, Vol.11, No. 4, 1996, pp.2038-2044.
- [13] S. Santoso, E. J. Powers and P. Hohann, "Power Quality Assessment via Wavelet Transform Analysis", *IEEE Trans. Power Delivery*, Vol. 11, No. 2, April 1996, pp. 924-930.
- [14] Youssef OAS, "A Wavelet-based Technique for Discrimination Between Faults and Magnetizing Inrush Currents in Transformers", *IEEE Transaction on Power Delivery* 2003, Vol. 18, No.1, pp.170-176.
- [15] Lin X, Liu P, Malik OP, "Studies for Identification of the Inrush Based on Improved Correlation Algorithm", *IEEE Trans. Power Delivery* 2002, Vol. 17, No. 4, pp. 901-907.